Parity-Violating and Parity-Conserving Asymmetries in Aluminum Scattering in the Qweak Experiment

Wouter Deconinck, for the Qweak Collaboration

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Bridging the Standard Model to New Physics
with the Parity Violation Program at MESA

WILLIAM & MARY
CHARTERED 1693

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Overview

Determination of the Weak Charge of the Proton

- Quick recap from David Armstrong's talk last week
- Highlight the reasons for aluminum and other measurements
- Explanation for non-ideal conditions of these measurements

Parity-Violating Ancillary Asymmetries

- Elastic scattering on aluminum at $E = 1.165\,\mathrm{GeV}$
- Inelastic scattering on hydrogen with $W = 2.2\,\mathrm{GeV}$

Parity-Conserving Transverse Asymmetries

- Elastic scattering on hydrogen
- Elastic scattering on aluminum, carbon

Thanks to numerous contributors/collaborators

- Kurtis Bartlett, Jim Dowd, Chuck Horowitz, Farrukh Fattoyev, Zidu Lin

Determination of the Weak Charge of the Proton

Qweak Experiment

- First experiment with direct access to proton's weak charge
- Experiment collected data between 2010 and 2012 with toroidal spectrometer and integrating quartz detectors

First determination based on subset of data

- Preliminary results were published in 2013 based on commissioning data[1] (4% compared to the independent full data set)

Long awaited final results are now here

- Final publication[2] in Nature on May 10, 2018
- Shocker! No disagreement with Standard Model

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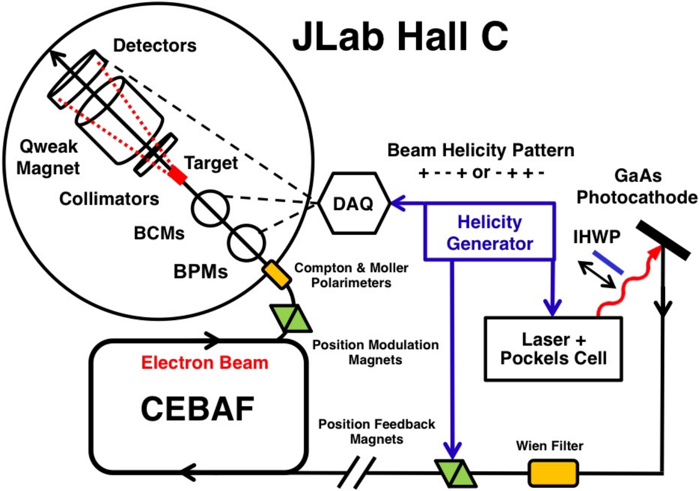
[1] *First Determination of the Weak Charge of the Proton, Phys. Rev. Lett. 111, 141803 (2013)*

[2] *Precision Measurement of the Weak Charge of the Proton, Nature 558 (2018)*

Determination of the Weak Charge of the Proton



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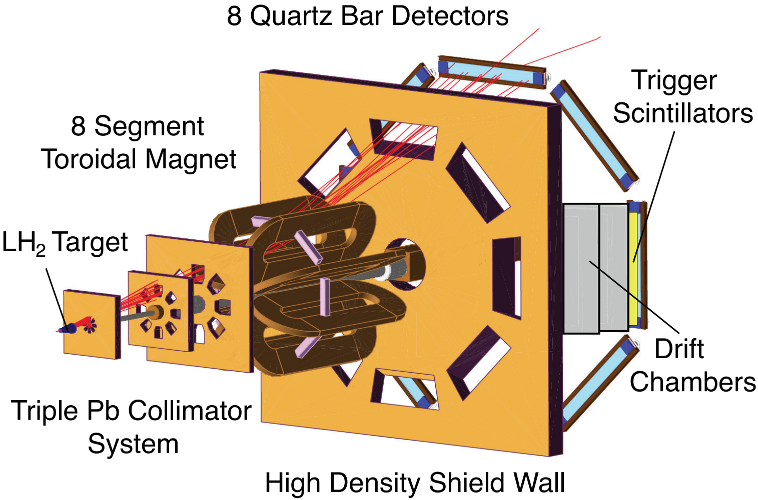
[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton



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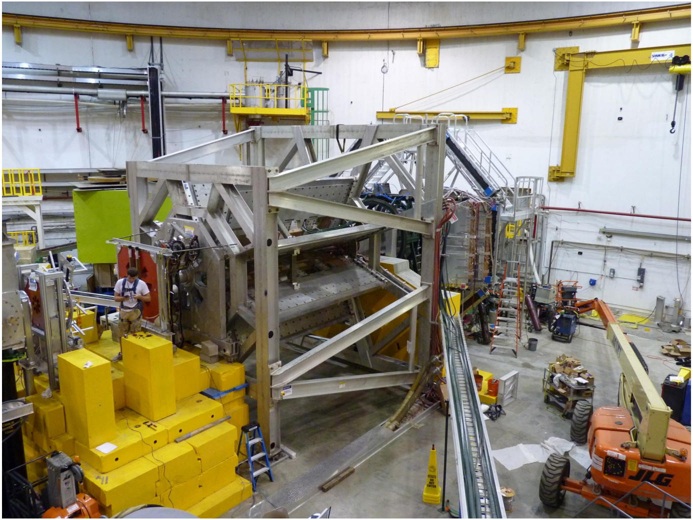
[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton



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[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton

Pushing the envelope of intensity (more detected electrons)

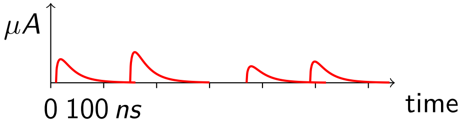
- Higher beam current (180 μA versus usually $<$ 100 μA)
- Longer cryo-target (35 cm versus 20 cm, 2.5 kW in 20 K LH2)
- Higher event rates up to 800 MHz (integrating mode)
- Typical luminosity of $1.7 \times 10^{39}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, $\int \mathcal{L} dt = 1\,\mathrm{ab}^{-1}$

Pushing the envelope of precision (better measurements)

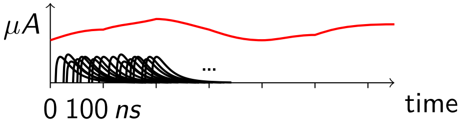
- Electron beam polarimetry precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level (beam position at nm level)
- Precise determination of Q^2 since $A_{PV} \propto Q^2$
- Isolate elastic scattering from background processes (f_i, A_i)
  - This is why we must measure various background asymmetries

Determination of the Weak Charge of the Proton

Event or counting mode



Integrating or current mode



- Each event individually detected, digitized and read-out
- Selection or rejection possible based on event characteristics
- 100 ns pulse separation limits rate to 10 MHz per detector segment; at least 1 day for 1 ppm precision

- Very high event rates possible, as long as detectors are linear
- But no rejection of background events possible after the fact
- Q_{Weak} segment rates 800 MHz; MOLLER segment rates up to 2.5 GHz; P2 up to 0.5 THz

Determination of the Weak Charge of the Proton

Background treatment in integrating experiments

- Measured asymmetry A_{msr} corrected for all background contributions
  - with their own parity-violating asymmetry A_i (ppm-level)
  - and their dilution in the measured asymmetry f_i (%-level)

$$A_{PV} = R_{total} \frac{\frac{A_{msr}}{P} - \sum f_i A_i}{1 - \sum f_i}$$

Unprecedented precision comes with inevitable surprises

- Discovered qualitatively new "beamline background"
  - Generated by scattering of helicity-dependent beam halo on clean-up collimator downstream of target and into detector acceptance
- Discovered qualitatively new "rescattering bias"
  - Spin precession of scattered electrons in spectrometer, followed by nuclear transverse spin azimuthal asymmetry when scattering in lead pre-radiators

Determination of the Weak Charge of the Proton

All uncertainties in ppb	Run 1	Run 2	Combined
Charge Normalization: A_{BCM}	5.1	2.3	
Beamline Background: A_{BB}	5.1	1.2	
Beam Asymmetries: A_{beam}	4.7	1.2	Note:
Rescattering bias: A_{bias}	3.4	3.4	correlations
Beam Polarization: P	2.2	(1.2)	between
Al target windows: A_{b1}	(1.9)	1.9	factors
Kinematics: R_{Q^2}	(1.2)	1.3	
Total of others $< 5\%$, incl ()	3.4	2.5	
Total systematic uncertainty	10.1	5.6	5.8
Total statistical uncertainty	15.0	8.3	7.3
Total combined uncertainty	18.0	10.0	9.3 (p = 86%)

$$A_{PV}(4\%) = -279 \pm 31(\text{syst}) \pm 35(\text{stat}) = -279 \pm 47(\text{total})$$

$$A_{PV}(\text{full}) = -226.5 \pm 5.8(\text{syst}) \pm 7.3(\text{stat}) = -226.5 \pm 9.3(\text{total})$$

Determination of the Weak Charge of the Proton

Intercept of A_{PV} at $Q^2 \to 0$ gives weak charge ($Q^2 = 0.025\,\mathrm{GeV}^2$)

$$\overline{A_{PV}} = \frac{A_{PV}}{A_0} = Q_W^p + Q^2 \cdot B(Q^2, \theta = 0) \quad \text{with} \quad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

Global fit[1] of all parity-violating electron scattering with full data set[2]

- Fit of parity-violating asymmetry data on H, D, ^{4}He, $Q^2 < 0.63\,\mathrm{GeV}^2$
- Free parameters were C_{1u}, C_{1d}, strange charge radius ρ_s and magnetic moment μ_s ($G_{E,M}^s \propto G_D$), and isovector axial form factor $G_A^{Z,T=1}$
- $Q_W^p(PVES)) = 0.0719 \pm 0.0045$, $\sin^2\theta_W(Q^2) = 0.2382 \pm 0.0011$
- $\rho_s = 0.19 \pm 0.11$, $\mu_s = -0.18 \pm 0.15$, $G_A^{Z,T=1} = -0.67 \pm 0.33$
- After combination with atomic parity-violation on Cs:
  - $C_{1u} = -0.1874 \pm 0.0022$
  - $C_{1d} = 0.3389 \pm 0.0025$

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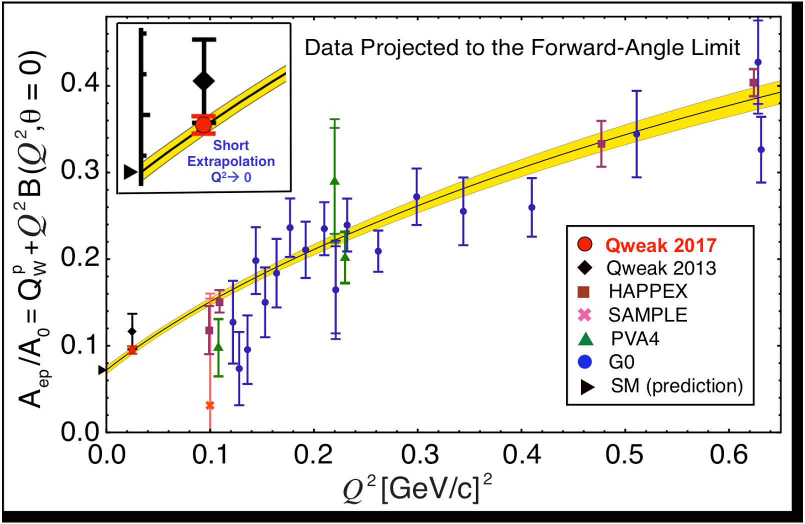
[1] *R. Young, R. Carlini, A.W. Thomas, J. Roche, Phys. Rev. Lett. 99, 122003 (2007)*

[2] *Precision Measurement of the Weak Charge of the Proton, Nature 558 (2018)*

Determination of the Weak Vector Charge of the Proton



Ancillary Measurements: Borne of Paranoia

Whatever could affect A_{PV} was measured and corrected for:

- Each background has asymmetry A_i and dilution f_i
- Non-hydrogen scattering: aluminum alloy of target windows
- Non-elastic contributions besides elastic *ep*: $N \to \Delta$, Møller
- Non-longitudinal polarization: horizontal, vertical transverse
- Non-electron particles reaching detector: π production
- Particles not originating from target: blocked octants
- Particles not reaching main detectors: superelastic region

Priorities driven by weak charge needs until final publication

- First: corrections on $A_{PV}(p)$ due to A_{PV}(Al alloy), B_n(H + Al alloy)
- Then: turn Al alloy into ^{27}Al for $A_{PV}(^{27}\mathrm{Al})$, extract B_n(H)
- Then: corrections due to B_n(Al alloy), extract $B_n(^{27}\mathrm{Al})$

Ancillary Measurements: Overview

Parity-Violating Ancillary Asymmetries

- Elastic scattering on aluminum at $E = 1.165\,\mathrm{GeV}$
- Inelastic scattering on hydrogen with $W = 2.2\,\mathrm{GeV}$

Parity-Conserving Transverse Asymmetries

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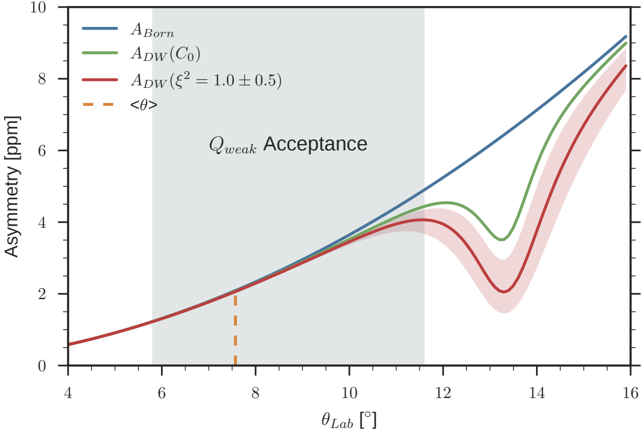
Ancillary Measurements: PV Asymmetry on Aluminum

Predictions of $A_{PV}(Al)$ using Distorted Wave calculation[1]



At Qweak's average acceptance, expect $A_{PV}(Al) \approx 2.1$ ppm ($E_{beam} = 1.16$ GeV).

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[1] *C. J. Horowitz Phys. Rev. C 89, 045503 (2014)*

Ancillary Measurements: PV Asymmetry on Aluminum

Available world data

- According to Horowitz a 4% measurement of the A_{PV} of pure ^{27}Al is sensitive to 2% changes in R_n.
- ^{27}Al's R_n (neutron distribution radius) helps benchmark theory that is important for other nuclei and astrophysics.

Predicted Qweak ^{27}Al results compared to PREx and CREx:

Exp.	Target	R_p[fm]	R_n[fm]	R_{ch}[fm]	$\mathbf{R_n - R_p}$[fm]	Ref
Q_{weak}	^{27}Al	2.904	2.913	3.013	**0.009** est.	1
PREx	^{208}Pb	5.45	$5.78^{+0.16}_{-0.18}$	5.50	$\mathbf{0.33^{+0.16}_{-0.18}}$	2
CREx	^{48}Ca	3.438	3.594	3.526	**0.156** est.	3

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[1] *Phys. Rev. C89, 045503 (2014)*

[2] *PRL 108, 112502 (2012)*

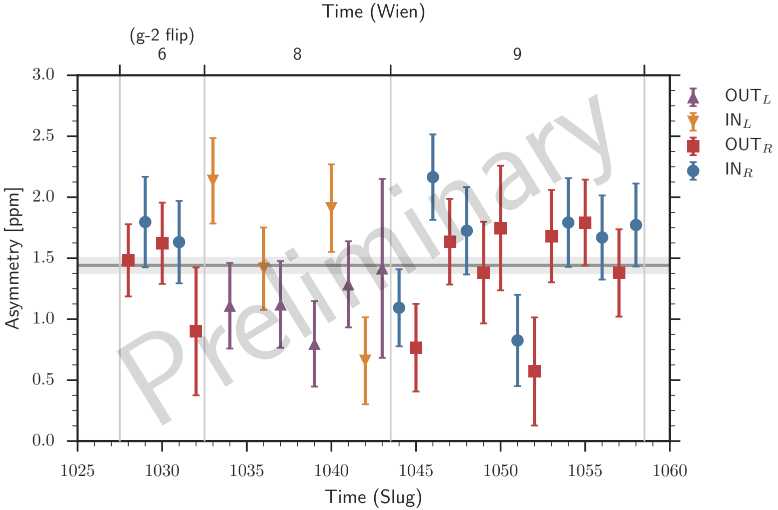
[3] *CC Calculations [CREx Proposal (2013)]*

Ancillary Measurements: PV Asymmetry on Aluminum

Experimental Conditions

- ^{27}Al data taken during two periods of $\mathrm{Q_{weak}}$ running:
  - Run 1: February–May 2011
  - Run 2: November 2011–May 2012
- Targets:
  - ^{27}Al alloy: 4.2 % X_0 (3.68 mm) thick
- Beam Conditions:
  - $E = 1.16$ GeV
  - $I = 60\text{-}70\ \mu$A
  - $P_L = 88\%$
- Spectrometer Conditions:
  - $<\theta> = 7.6^\circ$, $5.8^\circ \leq \theta \leq 11.6^\circ$
  - $<Q^2> \approx 0.024\ \mathrm{GeV}^2$
  - ≈ 150 MeV energy acceptance

Ancillary Measurements: PV Asymmetry on Aluminum



Uncorrected asymmetries with $\partial A_{msr}/A_{msr} = 4.7\%$(stat. only)

Ancillary Measurements: PV Asymmetry on Aluminum

Extraction of $A_{PV}(^{27}\text{Al})$

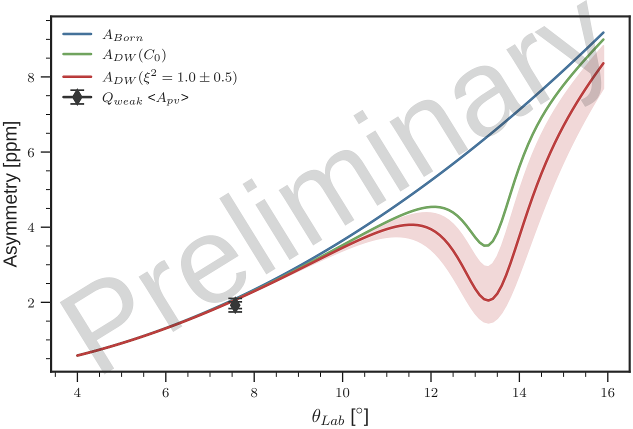
- Measurement/apparatus false asymmetry corrections typically on the order few ppb to 10s of ppb.
- Measurement/apparatus false asymmetry uncertainties of order few ppb. $A_{msr} = A_{raw} + A_{BCM} + A_{beam} + A_{BB} + A_L + A_T + A_{bias}$
- Largest uncertainties come from background asymmetries that dilute the elastic aluminum asymmetry.
  - Examples: quasi-elastic, inelastic ($N \rightarrow \Delta$), alloy elements (Zn, Mg,...), discrete excitations,...

$$A_{PV} = R_{tot} \frac{\frac{A_{msr}}{P} - \sum_i f_i A_i}{1 - \sum_i f_i}$$

- Background corrected asymmetry requires additional small corrections for acceptance, radiative energy loss, and light collection bias.

Ancillary Measurements: PV Asymmetry on Aluminum

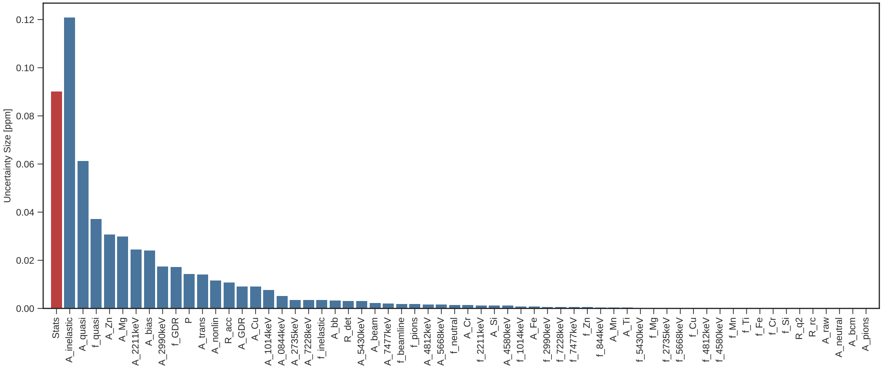
Preliminary Result of A_{PV}(Al)



$$A_{PV} = 1.924 \pm 0.180(\text{tot.})[0.090(\text{stat.}) \pm 0.156(\text{sys.})]\text{ppm} \quad \partial A/A = 9.4\%(\text{tot.})$$

Ancillary Measurements: PV Asymmetry on Aluminum

Statistical and Systematic Uncertainties



- Only $A_{inelastic}$ is larger than the statistical (red) uncertainty.

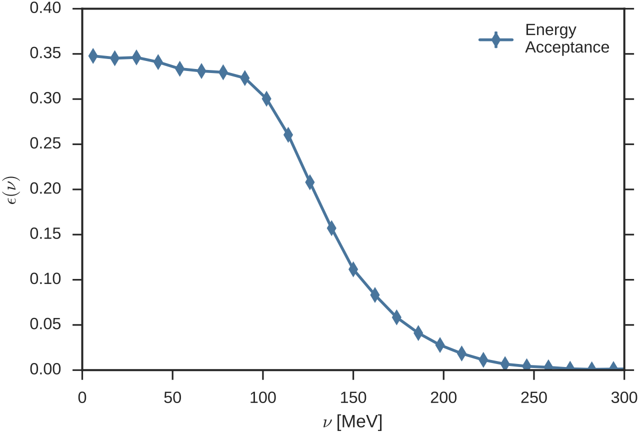
Ancillary Measurements: PV Asymmetry on Aluminum

Top five largest uncertainty contributions

Quantity	Error [ppm]
Statistics	0.090
A_{IN}: Inelastic Asym.	0.121
A_{QE}: Quasi-elastic Asym.	0.061
f_{QE}: Quasi-elastic Fraction	0.037
A_{Zn}: Zinc Asym.	0.031
A_{Mg}: Magnesium Asym.	0.030
$\vdots$	$\vdots$
Combined (quadrature)	0.180

Ancillary Measurements: PV Asymmetry on Aluminum

Large Energy Acceptance



Non-elastic scattering processes that dilute the asymmetry measurement.

Ancillary Measurements: PV Asymmetry on Aluminum

Quasi-Elastic and Inelastic Systematic Corrections

f_i: Background Fraction

$$f_i = \frac{y_i}{\sum_i y_i}$$

where y_i is the detector signal yield.

- Using Geant4 Monte Carlo simulation to determine y_i.
- Cross-section parameterization in simulation from empirical fit to data by P. Bosted and V. Mamyan (arXiv:1203.2262v2).

Process	$f[\%]$	$\partial f[\%]$	$\partial f/f[\%]$
Quasi	12.75	1.14	8.91
Inelastic	7.38	0.70	9.50

A_i: Background Asymmetry

- Quasi-elastic:
  - Theoretical support from Horowitz and Lin.
  - Initial calculation agrees well with "free nucleon" estimate.

$$A_{QE} = -0.34 \pm 0.34 \text{ ppm}$$

- Inelastic:
  - Have statistics dominated ($\partial A/A = 71$ %) measurement of this asymmetry.

$$A_{IN} = 1.61 \pm 1.15 \text{ ppm}$$

  - Possible theoretical calculation?

Ancillary Measurements: PV Asymmetry on Aluminum

Aluminum Alloy Elements

Aluminum Alloy Elements

Element	Run 1	Run 2
Al	89.53	89.23
Zn	5.90	5.87
Mg	2.60	2.63
Cu	1.50	1.81
Cr	0.19	0.19
Fe	0.14	0.11
Si	0.08	0.09
Mn	0.04	0.04
Ti	0.02	0.03

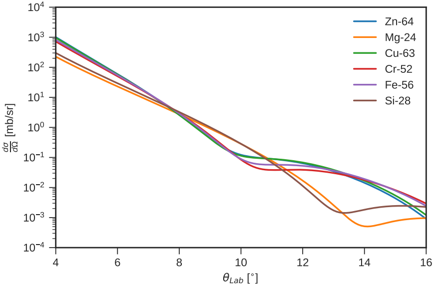
(Units: [w%])

- Considering only elastic scattering from alloy elements.
- Modifies the luminosity calculation.
- Zidu Lin has calculated the cross-sections and asymmetries using distorted wave model (for Zn, Mg, Cu, Cr, Fe, Si).
- Consider only common isotopes of Zn, Mg, Cu, Cr, Fe, and Si.
- Mn and Ti uses a Born approx. cross-section model, with Fourier-Bessel form factor fit.

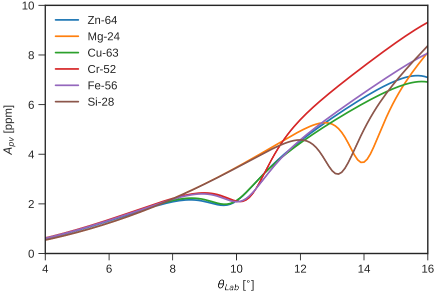
Ancillary Measurements: PV Asymmetry on Aluminum

Aluminum Alloy Elements

Rates/Yields Contributions:



Asymmetry:



- For Mn and Ti: using the Born approximation asymmetry: $A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}(Q_p + \frac{N}{Z} Q_n) \approx 2\text{ppm}$
    - Cross section uncertainty: 10% Zn-Si, 50% Mn and Ti
    - Asymmetry uncertainty: 50%

Ancillary Measurements: PV Asymmetry on Aluminum

Extraction of R_n

- Chuck, Farrukh, and Zidu calculated the correlation between R_n and A_{pv}. Using "ten distinct relativistic mean-field interactions". At a $Q^2 = 0.0235$ or $\approx 7.6^\circ$, assuming $\mathrm{E} = 1.160$ GeV.

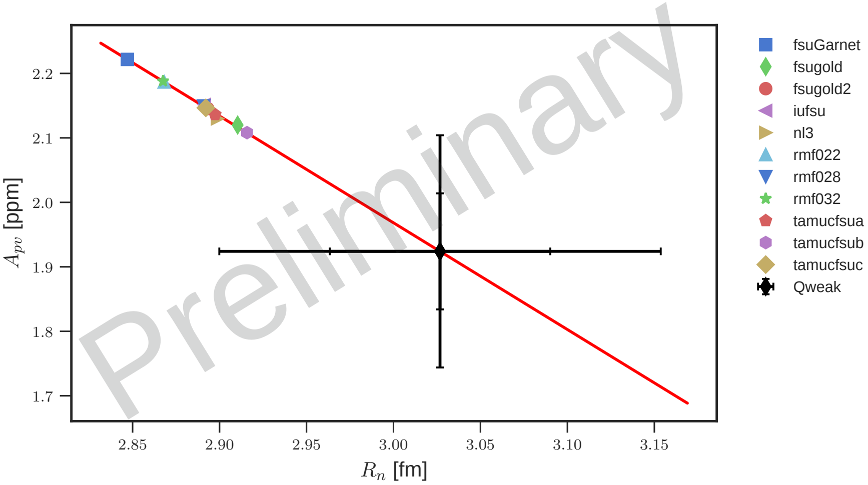
$$A_{pv} = -1.6555 R_n + 6.9347$$

- Extract R_n by inverting equation then use our A_{pv} as input.
- Relative uncertainty on R_n extracted with ln derivative.

$$\frac{\partial R_n}{R_n} = \frac{\partial A_{pv}}{A_{pv}} \div \frac{\partial \ln A_{pv}}{\partial \ln R_n} \quad \text{where } \frac{\partial \ln A_{pv}}{\partial \ln R_n} = 2.23252$$

$$R_n = 3.027 \pm 0.127 \mathrm{fm} \quad \frac{\partial R_n}{R_n} = 4.2\ [\%]$$

Ancillary Measurements: PV Asymmetry on Aluminum



Note: models very sensitive to kinematics (Q^2). Need final kinematics before this plot can be truly interpreted.

Ancillary Measurements: PV Asymmetry on Aluminum

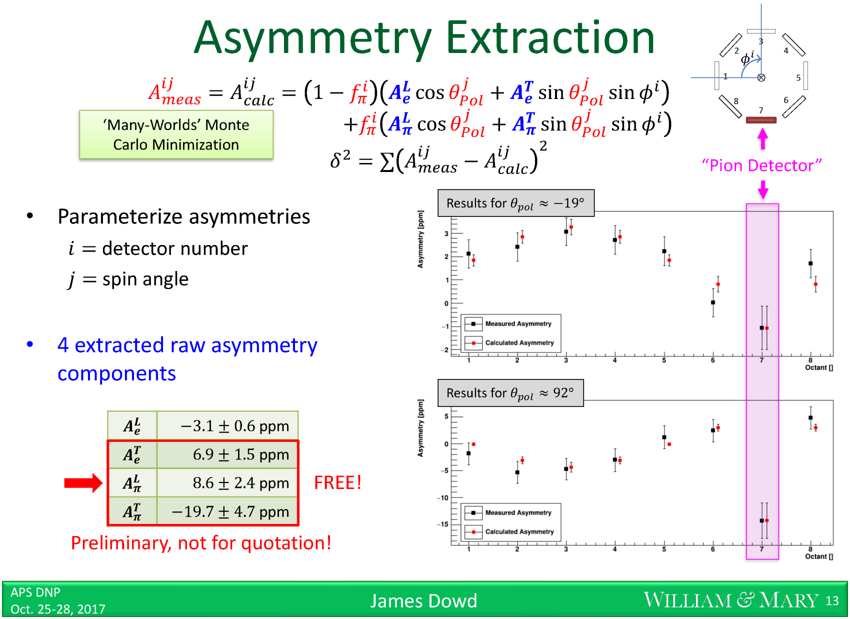
Skin Thickness, $R_n - R_p$

- Using a value of $R_p = 2.932$ fm from the set of relativistic mean field models.

$$\begin{aligned} R_n - R_p &= (3.027 \pm 0.127) - (2.932) \\ &= 0.095 \pm 0.127 \text{ [fm]} \end{aligned}$$

- Consistent with zero, which physically makes sense. Aluminum (Z = 13, N = 14) doesn't have a tremendous neutron excess.
- $A_{inelastic}$ contribution to A_{pv} is the reason for the large uncertainty in R_n and thus the skin thickness.
- Chuck's models predict a range of skin thicknesses: 0.004 fm – 0.024 fm.

Ancillary Measurements: PV Asymmetry at $W = 2.2$ GeV



Asymmetry Extraction

$$A^{ij}_{meas} = A^{ij}_{calc} = \left(1 - f^i_\pi\right)\left(A^L_e \cos\theta^j_{Pol} + A^T_e \sin\theta^j_{Pol} \sin\phi^i\right)$$
$$+ f^i_\pi\left(A^L_\pi \cos\theta^j_{Pol} + A^T_\pi \sin\theta^j_{Pol} \sin\phi^i\right)$$
$$\delta^2 = \sum\left(A^{ij}_{meas} - A^{ij}_{calc}\right)^2$$

‘Many-Worlds’ Monte Carlo Minimization

“Pion Detector”

- Parameterize asymmetries
  i = detector number
  j = spin angle

- 4 extracted raw asymmetry components

A^L_e	-3.1 ± 0.6 ppm
A^T_e	6.9 ± 1.5 ppm
A^L_π	8.6 ± 2.4 ppm
A^T_π	-19.7 ± 4.7 ppm

FREE!

Preliminary, not for quotation!

Results for $\theta_{pol} \approx -19°$

Results for $\theta_{pol} \approx 92°$

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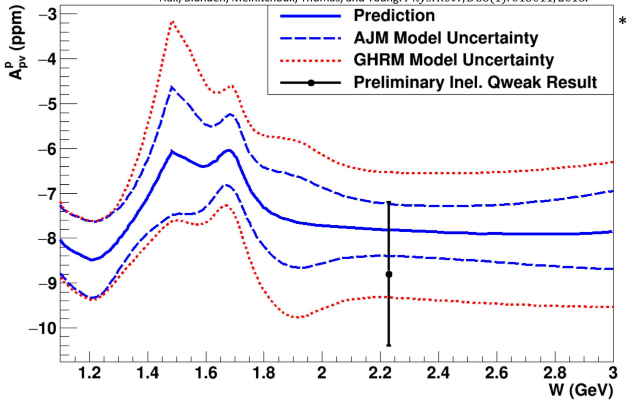
Ancillary Measurements: PV Asymmetry at $W = 2.2$ GeV

Preliminary Result

* Hall, Blunden, Melnitchouk, Thomas, and Young. *Phys. Rev.*, D88(1): 013011, 2013.



Model Predictions

$Q^2 = 0.09\ GeV^2$

$A^{p}_{PV} = -7.8 \pm 0.6$ ppm

$A^{p}_{PV} \approx -7.8 \pm 1.2$ ppm

Preliminary Result

$Q^2 = 0.075\ GeV^2$

$A_{phys} = -8.8 \pm 0.9(stat) \pm 1.3(syst)$ ppm

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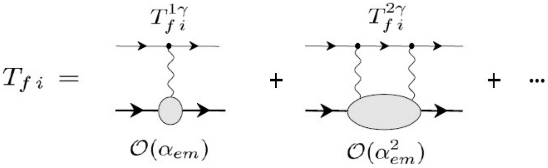
Ancillary Measurements: Transverse Asymmetry

Transverse single spin asymmetries

- Some transverse polarization, slightly broken azimuthal symmetry
- Measure with transversely polarized beam (H or V)
- Parity-conserving T-odd transverse asymmetry of order ppm

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\Im(T^{1\gamma *} \cdot AbsT^{2\gamma})}{|T^{1\gamma}|^2} \approx \mathcal{O}(\alpha\frac{m}{E}) \approx \text{ppm}$$



Ancillary Measurements: Transverse Asymmetry

Azimuthal asymmetries

$$A_T(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)} = B_n S \sin(\phi - \phi_S) = B_n (P_V \cos\phi + P_H \sin\phi)$$

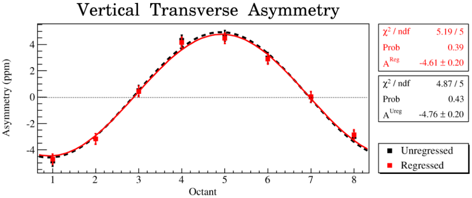
with $P_V = S \sin\phi_S$ and $P_H = S \cos\phi_S$

Available transverse single spin asymmetries

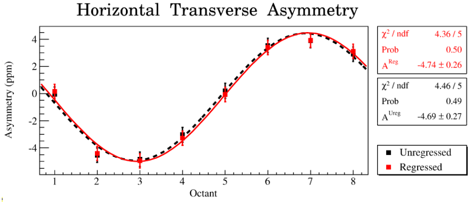
- Elastic $\vec{e}p$ in H, C, Al at $E = 1.165\,\mathrm{GeV}$
- Inelastic $\vec{e}p \to \Delta$ in H, C, Al at $E = 0.877\,\mathrm{GeV}$ and $1.165\,\mathrm{GeV}$
- Elastic $\vec{e}e$ in H at $E = 0.877\,\mathrm{GeV}$
- Deep inelastic $\vec{e}p$ in H at $W = 2.5\,\mathrm{GeV}$
- Pion photoproduction in H at $E = 3.3\,\mathrm{GeV}$

Ancillary Measurements: Transverse Asymmetry on H

Two hours of data taking in H: $A_T(oct) = A \sin\phi$

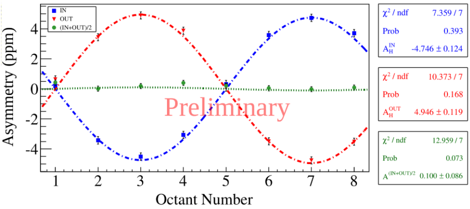


Two hours of data taking in V: $A_T(oct) = A \cos\phi$

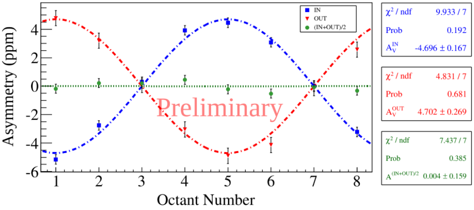


Ancillary Measurements: Transverse Asymmetry on H

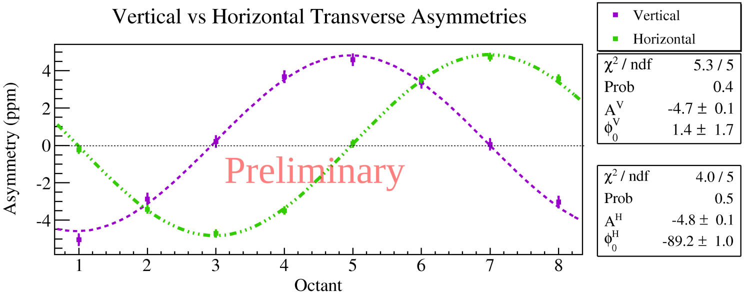
Cancellation with slow helicity reversal for H



Cancellation with slow helicity reversal for H



Ancillary Measurements: Transverse Asymmetry on H



- 90 degrees phase difference between H and V as expected
- Not corrected for polarization, backgrounds, acceptance,...

Ancillary Measurements: Transverse Asymmetry on H

- Background corrections (as for main experiment):

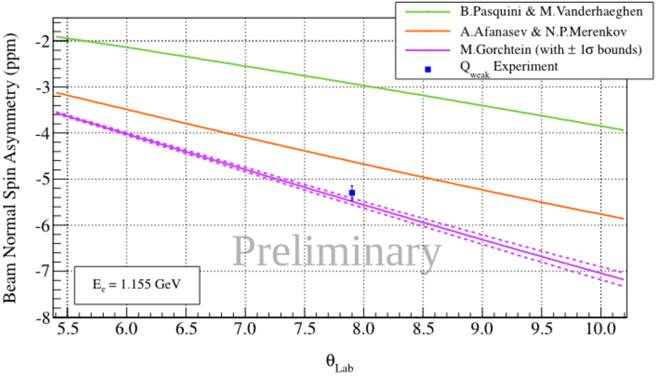
$$B_n = R_{total} \frac{\frac{A}{P} - \sum f_i A_i}{1 - \sum f_i}$$

- Measured corrections f_i and A_i for aluminum windows, $N \rightarrow \Delta$
- R_{total} includes radiative corrections, acceptance averaging, Q^2 variation with ϕ in each octant
- Most precise transverse asymmetry in *ep* in hydrogen (50 hours of data): $B_n = -5.35 \pm 0.07(\text{stat}) \pm 0.15(\text{syst})\,\text{ppm}$
- $\langle E \rangle = 1.155 \pm 0.003\,\text{GeV}$, $\langle \theta \rangle = 7.9 \pm 0.3\,\text{degrees}$

Ancillary Measurements: Transverse Asymmetry on H

Theoretical models:

- Pasquini, Vanderhaeghen, Phys. Rev. C 70, 045206 (2004)
- Afanasev, Merenkov, Phys. Lett. B 599, 48 (2004)
- Gorchtein, Phys. Rev. C 73, 055201 (2006)



Ancillary Measurements: Transverse Asymmetry on Al, C

Q_{Weak} wasn't made for this

- Large energy acceptance of spectrometer (150 MeV at 1.165 GeV)
- Nuclei are hardly ideal with low-lying levels

$B_n \approx -11\,\mathrm{ppm}$ in elastic scattering off C

- Analysis complete but no result released yet by collaboration
- Dissertation of Martin McHugh (GWU) is available on UMI and consistent with PREX at $1\,\sigma$
- Target is 99% ^{12}C, no significant contaminations
- Correction for contribution from quasi-elastic scattering
- No attempts at separation of nuclear excited states and GDR from elastic scattering
- B_n(C) is a quantity that does not correspond to a purely elastic state

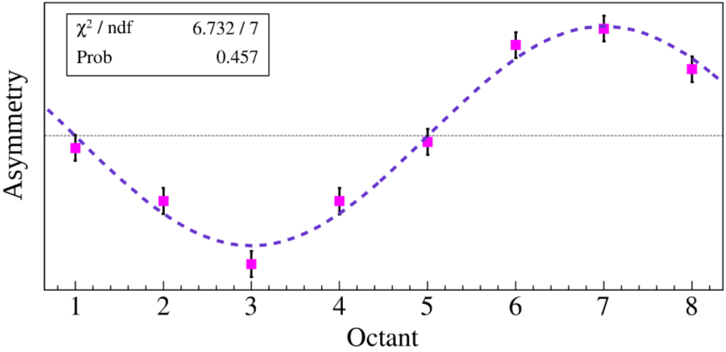
Ancillary Measurements: Transverse Asymmetry on Al, C

$B_n \approx [-11, -14]$ ppm in elastic scattering off ^{27}Al

- Some figures released by collaboration, no numbers, analysis nearing completion
- Alloy is a mixture with up to 10% other elements
- Attempts to treat quasi-elastic nuclear excited states and GDR more appropriately
- $B_n(^{27}\text{Al})$ will be interpretable as referring to a purely elastic state
- Work in progress by Kurtis Bartlett (W&M)

Ancillary Measurements: Transverse Asymmetry on Al

Aluminum azimuthal asymmetry is non-zero (uncorrected data)



- Aluminum alloy with ≈ 10% contaminations
- Corrections needed for quasielastic, $N \to \Delta$, nuclear excited states

Ancillary Measurements: Transverse Asymmetry on Al

Quasi-elastic scattering

- Free nucleon approximation and some heuristics related to isoscalar/isovector impact on sign of asymmetry
- More detailed quasi-elastic implementation per Horowitz, Phys. Rev. C 47, 826 (1992), which his grad student Zidu Lin has adapted to ^{27}Al

Contaminants in Al alloy

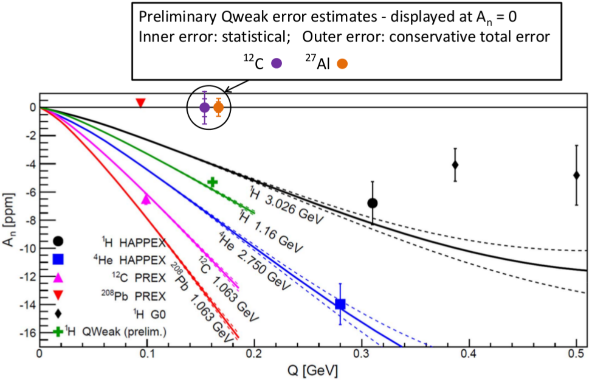
- Similar approach as Horowitz, Phys. Rev. C89, 045503 (2014)
- Implementation into Q_{Weak} Monte Carlo to determine contributions

Nuclear excited states

- Fitted nuclear excited state form factors using MIT Bates data
  - R.S. Hicks, A. Hotta, J.B. Flanz, H. deVries, Phys. Rev. C21, 2177 (1980)
  - P.J Ryan, R.S. Hicks, A. Hotta, J. Dubach, G.A. Peterson, D.V. Webb, Phys. Rev. C27, 2515 (1983)

Ancillary Measurements: Transverse Asymmetry on C, Al

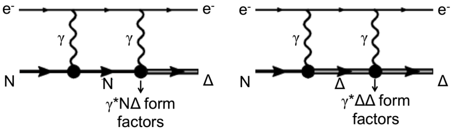
Projected uncertainties for B_n for C and Al


Preliminary Qweak error estimates - displayed at $A_n = 0$
Inner error: statistical; Outer error: conservative total error

- $B_n \propto AQ/Z$: Gorchtein, Horowitz, Phys. Rev. C77, 044606 (2008)
- HAPPEX, PREX: Abrahamyan *et al.*, PRL 109, 192501 (2012)

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$

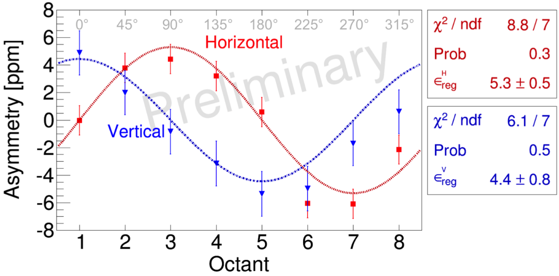
Access to the $\gamma^* \Delta\Delta$ form factor



- Large asymmetries in the forward region
- Several possible intermediate states N, Δ

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$

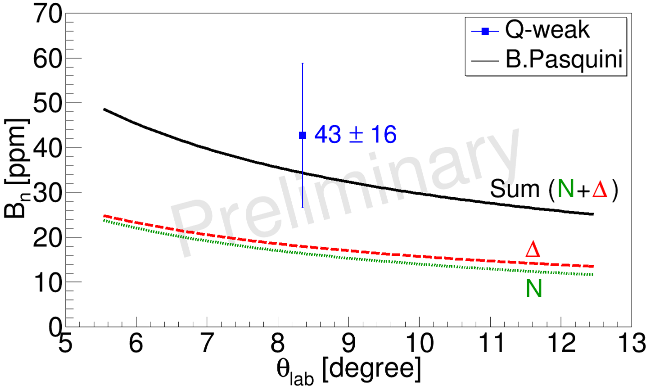
Before any background corrections



After background corrections

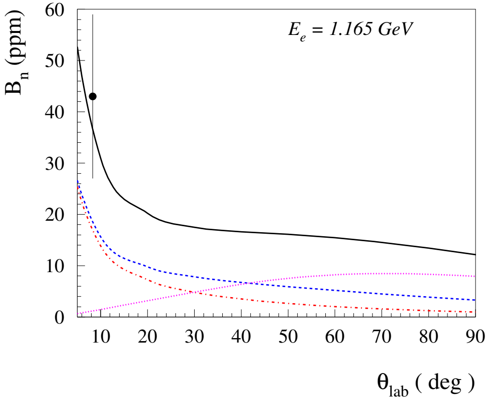
- Large radiative tail from elastic scattering as dilution with small asymmetry
- $B_n(N \to \Delta) = 43 \pm 16$ at $\langle\theta\rangle = 8.3$ degrees
- Nuruzzaman, CIPANP2015, arXiv:1510.00449 [nucl-ex]

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$



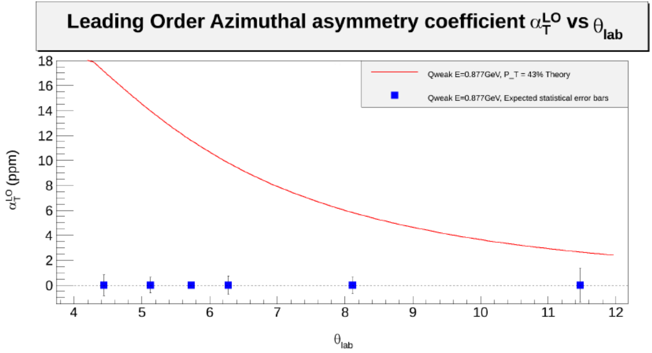
- Includes N and $\Delta(1232)$

Ancillary Measurements: Transverse Asymmetry in $N \to \Delta$



- Includes N, $\Delta(1232)$, $S11(1535)$, and $D13(1520)$
- Carlson, Pasquini, Pauk, Vanderhaeghen, arXiv:1708.05316 [hep-ph]

Ancillary Measurements: Transverse Asymmetry in Møller



- Dixon, Schreiber, Phys. Rev. D 69, 113001 (2004)

Qweak: More than the Proton's Weak Charge

Many ancillary measurements for which data is available:

A_{PV} helicity asymmetries:

- Elastic ^{27}Al
- $N \to \Delta$ (E of 1.16 GeV, 0.877 GeV)
- Near $W = 2.5\,\text{GeV}$ (for $\Box_{\gamma Z}$)
- Pion photoproduction (E of 3.3 GeV)

B_n transverse asymmetries:

- Elastic ep, ^{27}Al, C
- $N \to \Delta$
- Near $W = 2.5\,\text{GeV}$
- Pion photoproduction (E of 3.3 GeV)
- Møller

Topics for Discussion

Prioritization of ancillary analyses

- Currently in progress (or preliminary results):
  - B_n for ep
  - A_{PV} for $N \rightarrow \Delta$
  - A_{PV} for ^{27}Al
  - B_n for ^{27}Al, C

Additional Material

The Q_{Weak} Experiment: Kinematics in Event Mode

Reasons for a tracking system?

- Determine Q^2, note: $A_{meas} \propto Q^2 \cdot \left(Q_W^p + Q^2 \cdot B(Q^2)\right)$
- Main detector light output and Q^2 position dependence
- Contributions from inelastic background events

Instrumentation of only two octants

- Horizontal drift chambers for front region (Va Tech)
- Vertical drift chambers for back region (W&M)
- Rotation allows measurements in all eight octants

Track reconstruction

- Straight tracks reconstructed in front and back regions
- Front and back partial tracks bridged through magnetic field

The Q_{Weak} Experiment: Improved Beam Polarimetry

Requirements on beam polarimetry

- Largest experimental uncertainty in Q_{Weak} experiment
- Systematic uncertainty of 1% (on absolute measurements)

Upgrade existing Møller polarimeter ($\vec{e} + \vec{e} \to e + e$)

- Scattering off atomic electrons in magnetized iron foil
- Limited to separate, low current runs ($I \approx 1\,\mu$A)

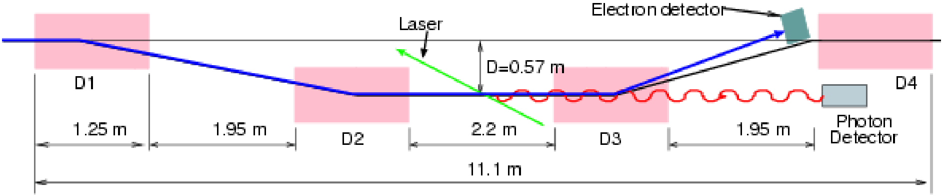
Construction new Compton polarimeter ($\vec{e} + \vec{\gamma} \to e + \gamma$)

- Compton scattering of electrons on polarized laser beam
- Continuous, non-destructive, high precision measurements

The Q_{Weak} Experiment: Improved Beam Polarimetry

Compton polarimeter

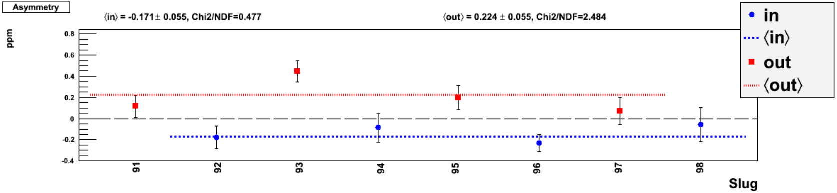
- Beam: 150 μA at 1.165 GeV
- Chicane: interaction region 57 cm below straight beam line
- Laser system: 532 nm green laser
  - 10 W CW laser with low-gain cavity
- Photons: $PbWO_4$ scintillator in integrating mode
- Electrons: Diamond strips with 200 μm pitch



Data Quality: Slow Helicity Reversal

$\lambda/2$-plate and Wien filter changes

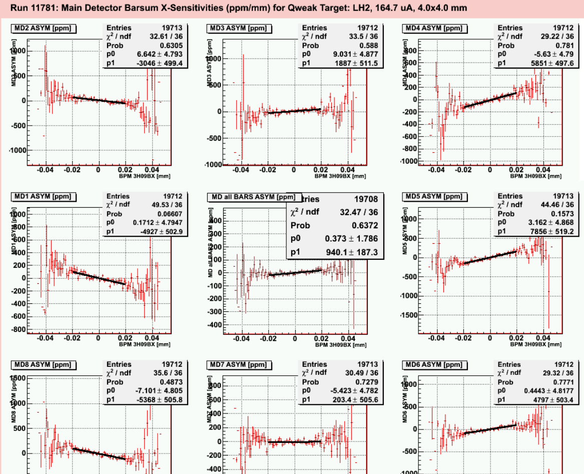
- Insertable $\lambda/2$-plate (IHWP) in injector allows 'analog' flipping helicity frequently
- Wien filter: another way of flipping helicity (several weeks)
- Each 'slug' of 8 hours consists of same helicity conditions



Helicity-Correlated Beam Properties Are Understood

Measured asymmetry depends on beam position, angle, energy

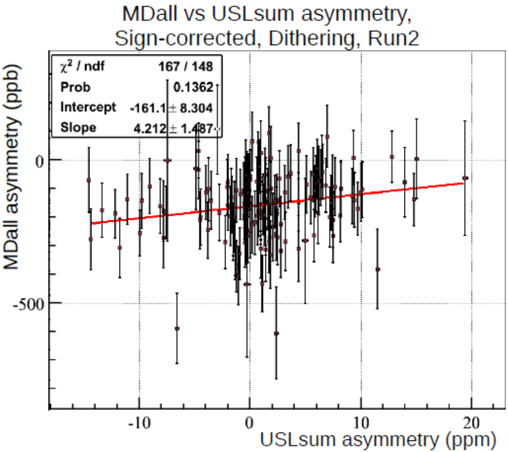
- Well-known and expected effect for PVES experiments
- “Driven” beam to check sensitivities from “natural” jitter


Run 11781: Main Detector Barsum X-Sensitivities (ppm/mm) for Qweak Target: LH2, 164.7 uA, 4.0x4.0 mm

However, Some Beamline Background Correlations Remain

After regression, correlation with background detectors

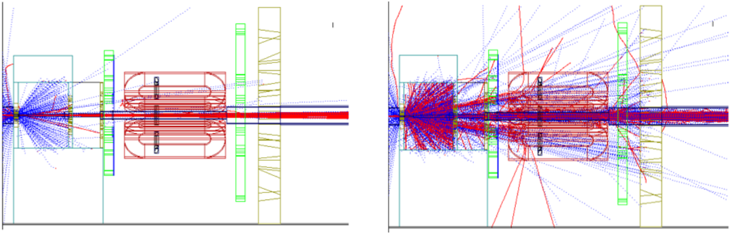
- Luminosity monitors & spare detector in super-elastic region
- Background asymmetries of up to 20 ppm (that's huge!)



Beamline Background Correlations Remain

Hard work by grad students: now understood, under control

- Partially cancels with slow helicity reversal (half-wave plate)
- Likely caused by large asymmetry in small beam halo or tails
- Scattering off the beamline and/or "tungsten plug"

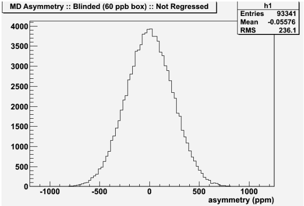


Qualitatively new background for PVES experiments at JLab

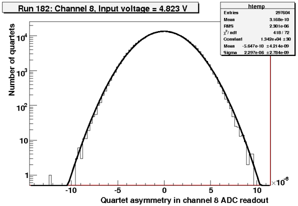
- Second regression using asymmetry in background detectors
- Measurements with blocked octants to determine dilution factor ($f_{b_2}^{MD} = 0.19\%$)

Data Quality: Understanding the Asymmetry Width

Asymmetry width



Battery width



Measurement

- 240 Hz helicity quartets $(+--+$ or $-++-)$
- Uncertainty $= RMS/\sqrt{N}$
- 200 ppm in 4 milliseconds
- $<$ 1 ppm in 5 minutes

Asymmetry width

- Pure counting statistics $\approx$ 200 ppm
- $+$ detector resolution $\approx$ 90 ppm
- $+$ current monitor $\approx$ 50 ppm
- $+$ target boiling $\approx$ 57 ppm
- $=$ observed width $\approx$ 233 ppm

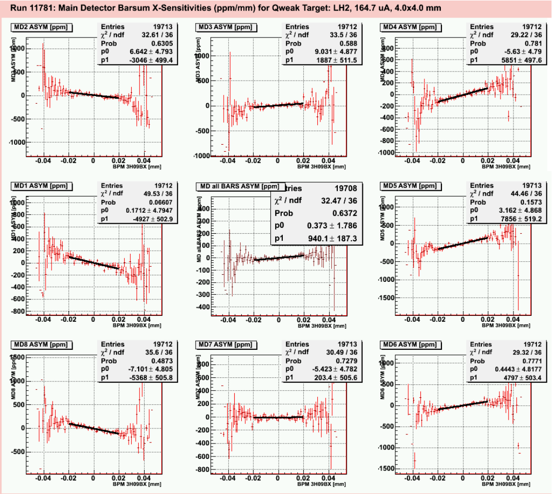
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles
- Linear regression:

$$A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$$

$$i = x, y, x', y', E$$



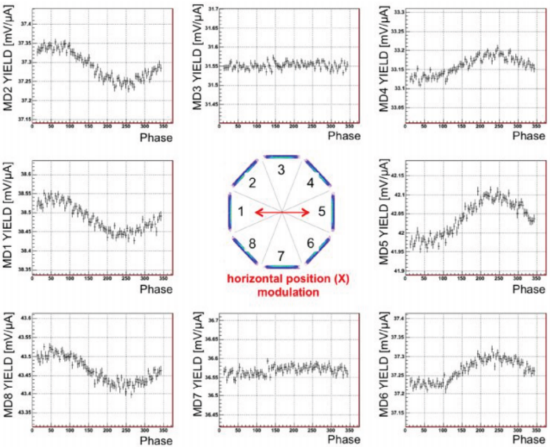
Data Quality: Helicity-Correlated Beam Properties

Natural beam motion

- Measured asymmetry correlated with beam position and angles
- Linear regression: $A_c = \sum_i \frac{\partial A}{\partial x_i} \Delta x_i$ $i = x, y, x', y', E$

Driven beam motion

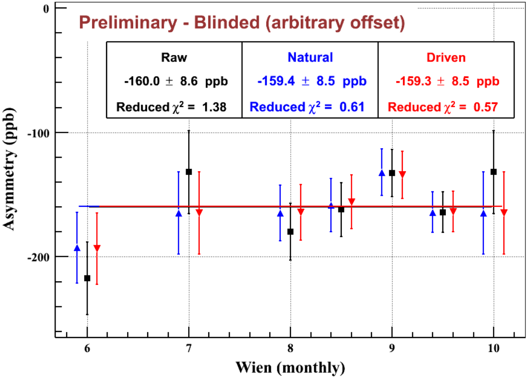
- Deliberate motion



horizontal position (X) modulation

Helicity-Correlated Beam Properties Are Understood

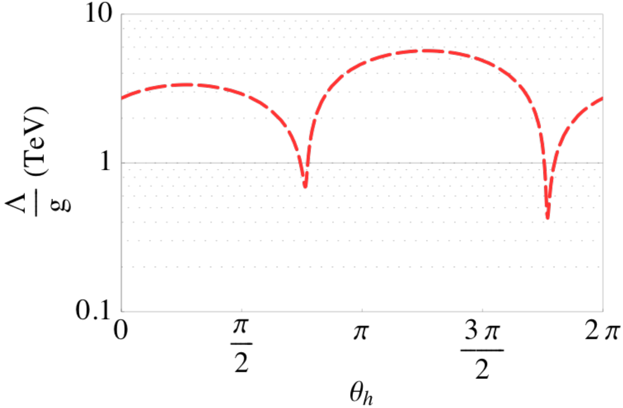
Excellent agreement between natural and driven beam motion


Run2 measured asymmetry

- Figure includes about 50% of total dataset for Q_{Weak} experiment
- No other corrections applied to this data

Sensitivity to New Physics

Lower bound on new physics (95% CL)

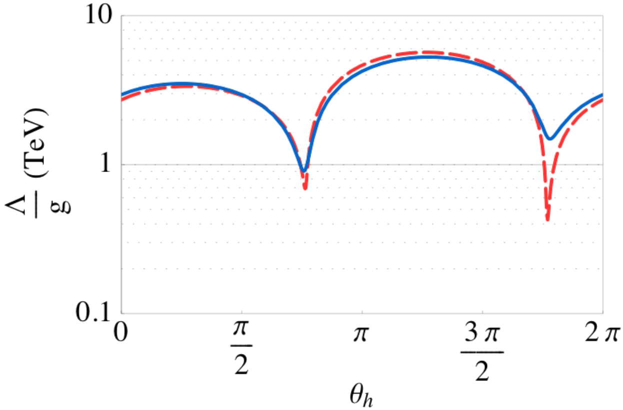


Constraints from

- Atomic PV: $\frac{\Lambda}{g} > 0.4\ TeV$

Sensitivity to New Physics

Lower bound on new physics (95% CL)

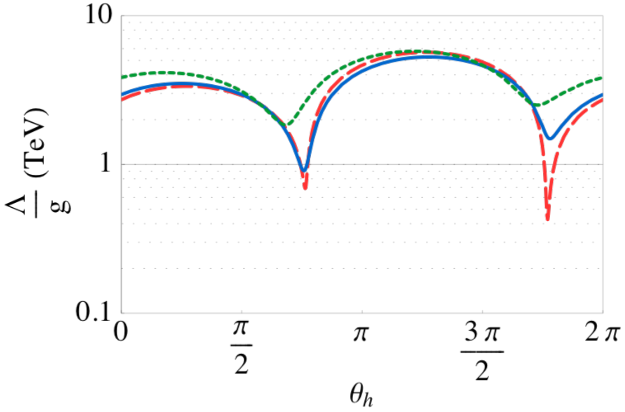


Constraints from

- Atomic PV: $\frac{\Lambda}{g} > 0.4\ TeV$
- PV electron scattering: $\frac{\Lambda}{g} > 0.9\ TeV$

Sensitivity to New Physics

Lower bound on new physics (95% CL)



Constraints from

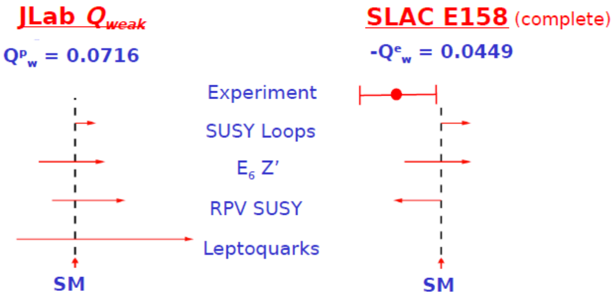
- Atomic PV: $\frac{\Lambda}{g} > 0.4\ TeV$
- PV electron scattering: $\frac{\Lambda}{g} > 0.9\ TeV$

Projection Q_{Weak}

- $\frac{\Lambda}{g} > 2\ TeV$
- 4% precision

Sensitivity to New Physics

Different experiments sensitive to different extensions



JLab Q_{weak}

$Q^p_w = 0.0716$

SLAC E158 (complete)

$-Q^e_w = 0.0449$

Experiment

SUSY Loops

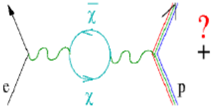
E_6 Z'

RPV SUSY

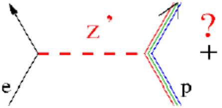
Leptoquarks

SM

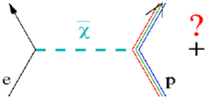
SM



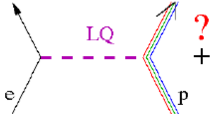
RPC SUSY



Generic Z'



RPV SUSY



Leptoquarks

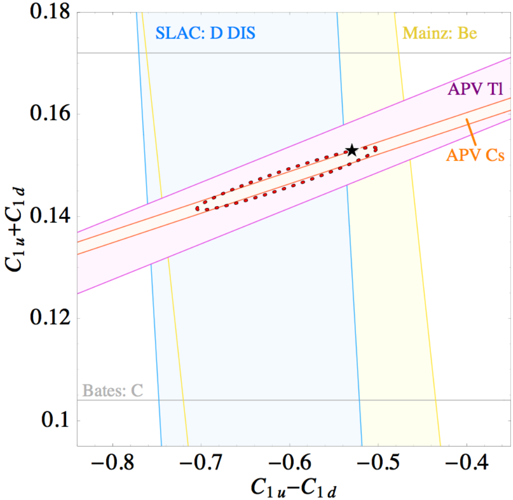
Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

$Q_W^p = -2(2C_{1u} + C_{1d})$

Early experiments

- SLAC and APV



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

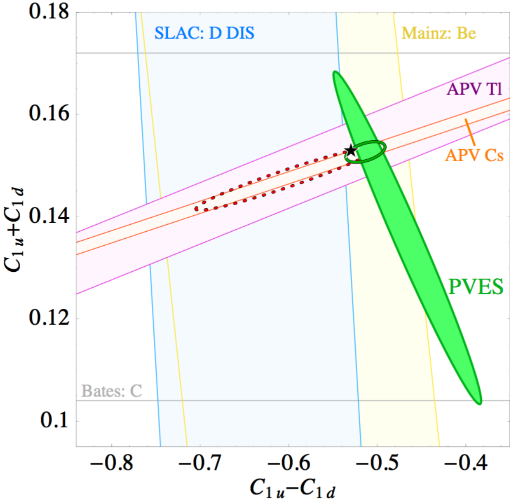
$Q_W^p = -2(2C_{1u} + C_{1d})$

Early experiments

- SLAC and APV

Electron scattering

- HAPPEx, G0
- PVA4/Mainz
- SAMPLE/Bates



Parity-Violating Electron Scattering: Quark Couplings

Weak vector charge *uud*

$Q_W^p = -2(2C_{1u} + C_{1d})$

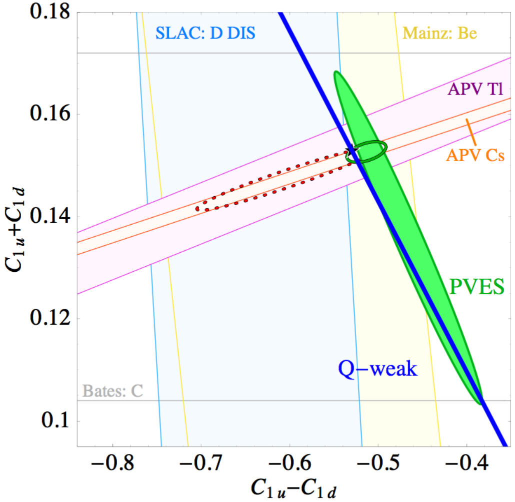
Early experiments

- SLAC and APV

Electron scattering

- HAPPEx, G0
- PVA4/Mainz
- SAMPLE/Bates

Q_{Weak} experiment



Precision Electroweak Experiments: JLab 12 GeV

MOLLER Experiment

Source	ΔA_{PV}
Mom. transfer Q^2	0.5%
Beam polarization	0.4%
2nd order beam	0.4%
Inelastic *ep*	0.4%
Elastic *ep*	0.3%

SoLID PV-DIS Experiment

Source	ΔA_{PV}
Beam polarization	0.4%
Rad. corrections	0.3%
Mom. transfer Q^2	0.5%
Inelastic *ep*	0.2%
Statistics	0.3%

Precision beam polarimetry is crucial to these experiments.

Precision Electroweak Experiments: Polarimetry

Compton Polarimetry

- $\vec{e}\vec{\gamma} \to e\gamma$ (polarized laser)
- Detection e and/or γ
- Only when beam energy above few hundred MeV
- High photon polarization but low asymmetry
- Total systematics $\sim 1\%$
    - laser polarization
    - detector linearity

Møller Polarimetry

- $\vec{e}\vec{e} \to ee$ (magnetized Fe)
- Low current because temperature induces demagnetization
- High asymmetry but low target polarization
- Levchuk effect: scattering off internal shell electrons
- Intermittent measurements at different beam conditions
- Total systematics $\sim 1\%$

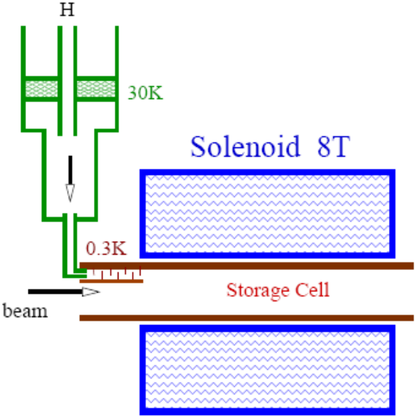
Atomic Hydrogen Polarimetry

New polarimetry concept[1]

- 300 mK cold atomic H
- 8 T solenoid trap
- $3 \cdot 10^{16}$ atoms/cm^2
- $3 \cdot 10^{15-17}$ atoms/cm^3
- 100% polarization of e

Advantages

- High beam currents
- No Levchuk effect
- Non-invasive, continuous



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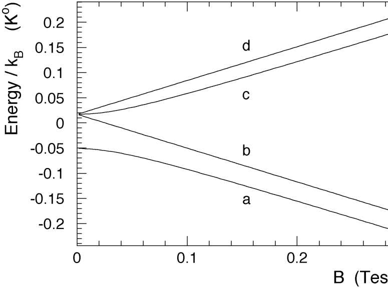
[1] *E. Chudakov, V. Luppov, IEEE Trans. on Nucl. Sc. 51, 1533 (2004).*

Atomic Hydrogen Polarimetry: 100% Polarization of e

Hyperfine Splitting in Magnetic Field

- Energy splitting of $\Delta E = 2\mu B$:
  $\uparrow / \downarrow = \exp(-\Delta E/kT) \approx 10^{-14}$
- Low energy states with $|s_e s_p\rangle$:
  - $|d\rangle = |\uparrow\Uparrow\rangle$
  - $|c\rangle = \cos\theta\,|\uparrow\Downarrow\rangle + \sin\theta\,|\downarrow\Uparrow\rangle$
  - $|b\rangle = |\downarrow\Downarrow\rangle$
  - $|a\rangle = \cos\theta\,|\downarrow\Uparrow\rangle - \sin\theta\,|\uparrow\Downarrow\rangle$
  - with $\sin\theta \approx 0.00035$



- $P_e(\downarrow) \approx 1$ with only 10^5 dilution from $|\uparrow\Downarrow\rangle$ in $|a\rangle$ at $B = 8\,\mathrm{T}$
- $P_p(\Uparrow) \approx 0.06$ because 53% $|a\rangle$ and 47% $|b\rangle$
- Force $\vec{\nabla}(-\vec{\mu} \cdot \vec{B})$ will pull $|a\rangle$ and $|b\rangle$ into field

Atomic Hydrogen Polarimetry: Expected Contaminations

Without beam

- Recombined molecular hydrogen suppressed by coating of cell with superfluid He, $\sim 10^{-5}$
- Residual gasses, can be measured with beam to $< 0.1\%$

With $100\,\mu$A beam

- 497 MHz RF depolarization for 200 GHz $|a\rangle \to |c\rangle$ transition, tuning of field to avoid resonances, uncertainty $\sim 2 \cdot 10^{-4}$
- Ion-electron contamination: builds up at 20%/s in beam region, cleaning with $\vec{E}$ field of $\sim 1\,$V/cm, uncertainty $\sim 10^{-5}$

Atomic Hydrogen Polarimetry: Projected Uncertainties

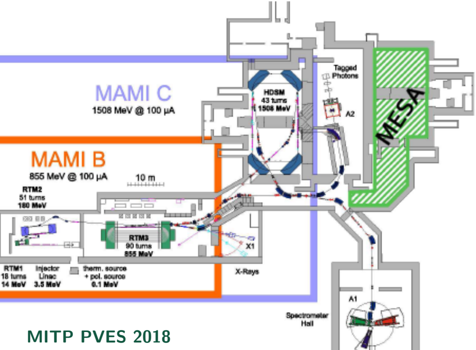
Projected Systematic Uncertainties ΔP_e in Møller polarimetry

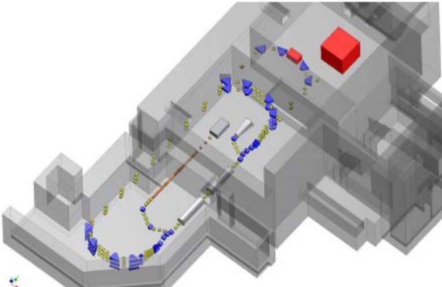
Source	Fe-foil	Hydrogen
Target polarization	0.63%	0.01%
Analyzing power	0.30%	0.10%
Levchuk effect	0.50%	0.00%
Deadtime	0.30%	0.10%
Background	0.30%	0.10%
Other	0.30%	0.00%
Unknown unknowns	0.00%	0.30%(?)
Total	1.0%	0.35%

Atomic Hydrogen Polarimetry: Collaboration with Mainz

P2 Experiment in Mainz: Weak Charge of the Proton

- "Q_{Weak} experiment" with improved statistical precision
- Dedicated 200 MeV accelerator MESA under construction
- Required precision of electron beam polarimetry $< 0.5\%$
- Strong motivation for collaboration on a short timescale (installation in 2017)

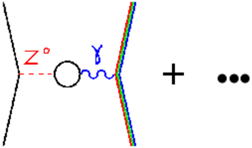


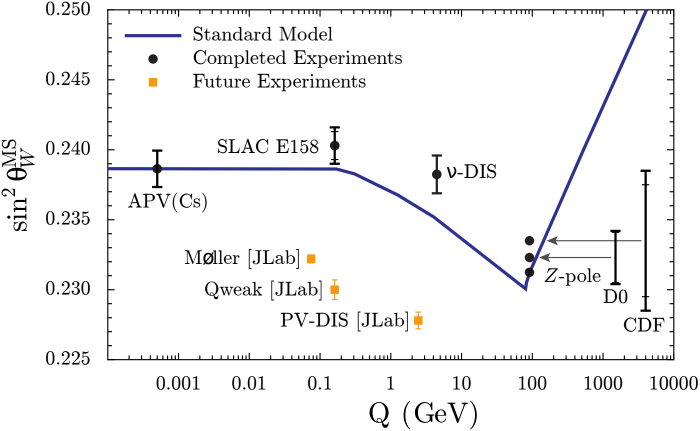


Parity-Violating Electron Scattering: Running of Weak Mixing Angle

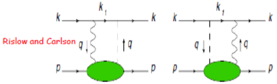
Running of $\sin^2\theta_W$ ($Q^p_W = 1 - 4\sin^2\theta_W$)

- Higher order loop diagrams
- $\sin^2\theta_W$ varies with Q^2





γZ Box Corrections near 1.16 GeV



In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

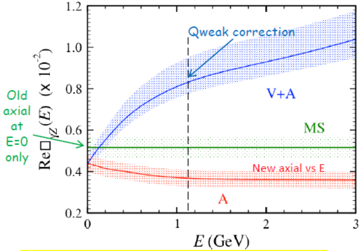
This soon led to more refined calculations with corrections of ~8% and error bars ranging from ±1.1% to ±2.8%.

It will probably also spark a refit of the global PVES database used to constrain G_E^s, G_M^s, G_A.

PV Amplitude	**Authors**	**Correction* @ E=1.165 (GeV)**
$A^e \times V^p$ (vanishes as E→0)	GH	0.0026+-0.0026**
	SBMT	$0.0047^{+0.0011}_{-0.0004}$
	RC	0.0057±0.0009
	GHR-M	0.0054±0.0020
$V^e \times A^p$ (finite as E→0)	MS (as updated by EKR-M)	0.0052±0.0005***
	BMT	0.0037±0.0004

*Does not include a small contribution from the elastic.
** 5.7%×Q_w^p(LO) = 0.0026. Q_w^p(LO) = 0.04532.
***Included in Q_w^p. For reference, Q_w^p =0.0713(8).

BMT and references
(V and A are hadronic couplings)

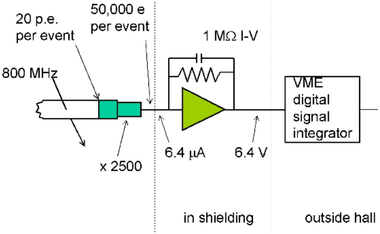


Forthcoming axial results for Q_w^n have the potential to impact the interpretation of Cs APV.

γZ Box Corrections near 1.16 GeV
A Partial Bibliography

PV Amplitude	Authors	Reference
$A^e \times V^p$ (vanishes as E→0)	GH	Gorchtein & Horowitz, PRL **102**, 091806 (2009)
	SBMT	Sibirtsev, Blunden, Melnitchouk, andThomas, PRD **82**, 013011 (2010)
	RC	Rislow & Carlson, PRD **83**, 113007 (2011)
	GHR-M	Gorchtein, Horowitz, and Ramsey-Musolf, PRC **84**, 015502 (2011)
$V^e \times A^p$ (finite as E→0)	MS	Marciano and Sirlin, PRD **27**, 552 (1983), PRD **29**, 75 (1984)
	EKR-M	Erler, Kurylov, and Ramsey-Musolf, PRD **68**, 016006 (2003)
	BMT	Blunden, Melnitchouk, and Thomas, PRL **107**, 081801 (2011)

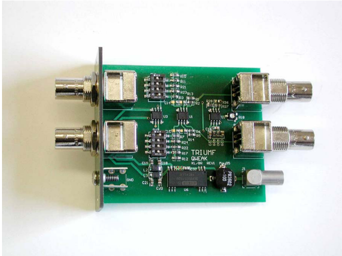
The Q_{Weak} Experiment: Main Detector



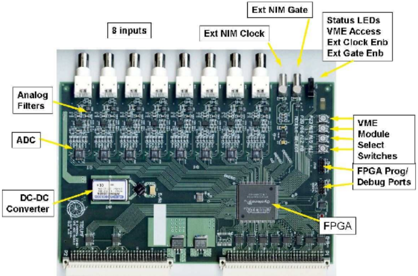
Low noise electronics

- Event rate: 800 MHz/PMT
- Asymmetry of only 0.2 ppm
- Low noise electronics (TRIUMF)

I-V Preamplifier



18-bit 500 kHz sampling ADC



The Q_{Weak} Experiment: Systematic Uncertainties

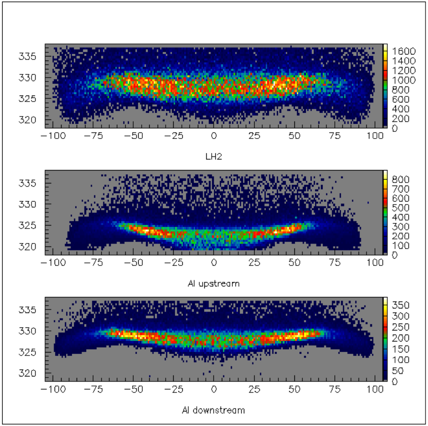
Reminder: weak vector charges

- Proton weak charge $Q_W^p \approx -0.072$
- Neutron weak charge $Q_W^n = -1$

Sources of neutron scattering

- Al target windows
- Secondary collimator events
- Small number of events, but huge false PV asymmetry

Al target windows



Electroweak Interaction: Running of Weak Mixing Angle

Atomic parity-violation on ^{133}Cs

- Porsev, Beloy, Derevianko[1]: Updated calculations in many-body atomic theory
- Experiment: $Q_W(^{133}\mathrm{Cs}) = -73.25 \pm 0.29 \pm 0.20$
- Standard Model: $Q_W(^{133}\mathrm{Cs}) = -73.16 \pm 0.03$

NuTeV anomaly

- Reported $3\,\sigma$ deviation from Standard Model
- Erler, Langacker: strange quark PDFs
- Londergan, Thomas[2]: charge symmetry violation, $m_u \neq m_d$
- Cloet, Bentz, Thomas[3]: in-medium modifications to PDFs, isovector EMC-type effect

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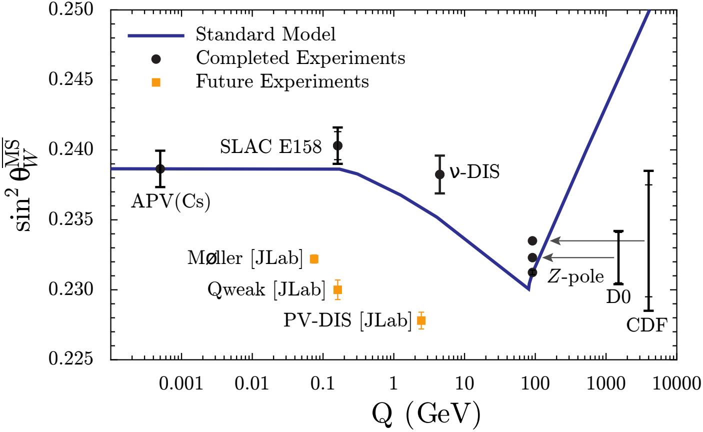
[1] *Phys. Rev. Lett. 102 (2009) 181601*

[2] *Phys. Rev. D67 (2003) 111901*

[3] *Phys. Lett. B693 (2010) 462-466*

NuTeV Nuclear Correction

Isovector EMC effect[1] affects NuTeV point[2]



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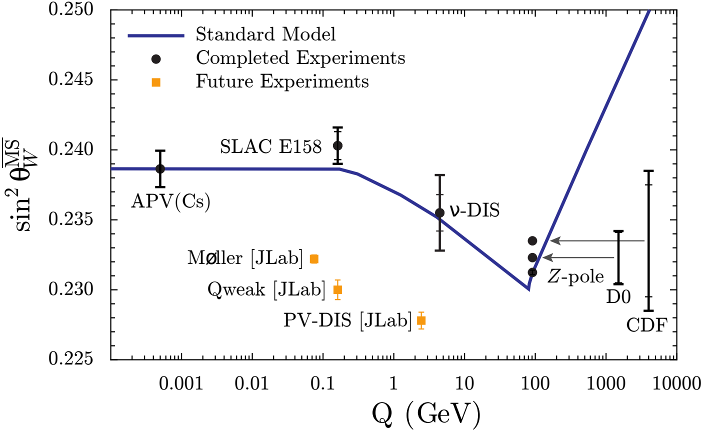
[1] *I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)*

[2] *W. Bentz, Phys. Lett. B693, 462-466 (2010)*

NuTeV Nuclear Correction

Isovector EMC effect[1] affects NuTeV point[2]



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[1] *I. Cloët, W. Bentz, A. M. Thomas, Phys. Rev. Lett. 102, 252301 (2009)*

[2] *W. Bentz, Phys. Lett. B693, 462-466 (2010)*